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RESEARCH MEMORANDUM

for the

Air Materiel Command, U. S. Air Force

CALIBRATION OF AIR-FLOW METERS FOR J33 COMPRESSOR INVESTIGATION

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

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SUMMARY

Flow-metering devices used by the NACA and by the manufacturer of the J33 turbojet engine were calibrated together to determine whether an observed discrepancy in weight flow of approximately 4 percent for the two separate investigations might be due to the different devices used to meter air flow. A commercial adjustable orifice and a square-edge flat-plate orifice used by the NACA and a flow nozzle used by the manufacturer were calibrated against surveys across the throat of the nozzle. It was determined that over a range of weight flows from 18 to 45 pounds per second the average weight flows measured by the metering device used for the compressor test would be 0.70 percent lower than those measured by the metering device used in the engine tests and the probable variation about this mean would be ±0.39 percent. The very close agreement of the metering devices shows that the greater part of the discrepancy in weight flow is attributable to the effect of inlet pressure.

INTRODUCTION

At the request of the Air Materiel Command, U. S. Air Force, an investigation is being conducted at the NACA Cleveland laboratory to determine the performance characteristics of a series of J33 turbojet-engine compressors. Engine tests by the manufacturer and component tests by the NACA with the 17-blade impeller of the J33-A-23 compressor (reference 1) produced different values of weight flow, which may have been caused by errors in flow metering or by the fact that the two investigations had to be conducted at different inlet pressures. In order to determine the magnitude of the differences resulting from the air-flow metering devices, the commercial adjustable orifice and the submerged, flat-plate, square-edge orifice used by the NACA, and a flow nozzle used by the manufacturer were calibrated against weight flows from surveys across the nozzle throat. The weight flows ranged from 18 to 45 pounds per second.

INSTRUMENTATION

Two separate systems, which were actually the two alternate inlet systems available for the J33 turbojet engine compressors, were used in the present study. One system contained a commercial adjustable orifice and the other a submerged, flat-plate, square-edge orifice. The flow nozzle could be connected at the inlet of either system and air was drawn through these systems by the laboratory exhaust facilities. All temperatures were read on a calibrated potentiometer in conjunction with a spotlight galvanometer.

Flat-plate orifice. - The 18.394-inch-diameter orifice was mounted in a 40.88-inch-diameter pipe as shown in figure 1; two 1/8-inch-diameter corner static-pressure taps were located $1\frac{1}{4}$ inches upstream of the orifice, and two were located $1\frac{1}{4}$ inches downstream of the orifice. One upstream and one downstream tap were connected to a differential water manometer and the upstream tap was also connected to an absolute-reading mercury manometer. The other two taps were connected to a separate differential water manometer as a check. Two total-temperature thermocouples were located 1 pipe diameter upstream of the orifice plate on diametrically opposite sides of the pipe and extended into the pipe one-third the pipe diameter.

Adjustable orifice. - The 20-inch adjustable orifice had an upstream and downstream static-pressure tap as an integral part of the flow-meter body. The pressure drop across the orifice was measured on a differential water manometer and the upstream tap was connected to an absolute-reading mercury manometer. A total-temperature thermocouple was located approximately 3 pipe diameters upstream of the orifice and extended into the pipe one-half the pipe diameter.

Flow nozzle. - The instrumentation of the flow nozzle is shown in figure 2. Mounted at the upstream face of the nozzle was a wooden panel to simulate the nozzle installation in engine tests by the manufacturer. The upstream instrumentation consisting of four static-pressure taps and four total-temperature thermocouples was mounted on the wooden panel. Four static-pressure taps were located 90° apart in the throat of the nozzle as shown in figure 3. All of the static-pressure taps were connected to individual water manometers.

A movable total-pressure probe (fig. 4) was located at the throat of the nozzle in the plane of the static-pressure taps. This probe could be accurately positioned at each of the 36 measuring stations across the nozzle throat and could be moved to any one of four positions at 45° intervals (fig. 3).

The probe was connected to one of the static-pressure taps in the nozzle throat through a differential water manometer. A calibrated microbarograph was used to measure the total pressure upstream of the nozzle. A fixed total-pressure probe in the throat of the nozzle indicated variations in flow during each survey.

All pressures were corrected for changes in density of the measuring fluids by the method recommended in reference 2. The precision of the measurements is estimated to be within the following limits:

Temperature, °F	±0.5
Pressure, inches mercury absolute	±0.04
Pressure, inches water absolute	±0.1

METHODS OF COMPUTING WEIGHT FLOW

Surveys across nozzle throat. - The static pressure for each run was determined by averaging the readings from the four throat static-pressure taps. The dynamic pressure at each survey station was the difference, corrected for compressibility, between the total pressure from the survey probe and the throat static pressure. Because the first measuring station was 0.015 inch from the wall the velocity distribution between the station and the wall was not known. In this investigation a constant velocity, equal to the velocity at the station, was assumed between the station and the wall. This assumption of velocity distribution will introduce negligible variations in weight flow when compared with the weight flows obtained assuming the 1/7 power-law velocity distribution between the first measuring station and the wall. The nozzle-throat area was divided into annular rings by taking one-half the radial distance between survey stations as the boundaries for these rings. The weight flow through each of these annular rings was determined from the compressible-flow equation

$$W = \frac{\Delta P}{\sqrt{RT}} \left(\frac{p}{P}\right)^{\frac{\gamma+1}{2\gamma}} \sqrt{\gamma g} \sqrt{\frac{2}{\gamma-1}\left[\left(\frac{P}{p}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$$

where

W weight flow, pounds per second

A area of annular ring, square feet

P total pressure, pounds per square foot

T total temperature upstream of nozzle, °R

p static pressure, pounds per square foot

R gas constant

γ ratio of specific heats

g gravitational constant, feet per second per second

The flows through each annular ring were added to obtain the total weight flow through the nozzle for each survey-probe position. The flows for the four probe positions were averaged to obtain the weight flow for each survey point.

Flat-plate orifice. - The weight flow through the flat-plate orifice was computed from the standard formula (reference 3):

$$W = 0.668\ A_2\ K\ E\ Y\ \sqrt{\rho_1 \Delta p}$$

where

K coefficient of discharge or flow coefficient including approach factor

E area constant for thermal expansion of orifice

Y empirical expansion factor for compressible fluids

ρ_1 density at inlet of orifice, pounds per cubic foot

Δp pressure drop across orifice, pounds per square inch

The subscript 2 indicates the orifice. The value of E is 1.00. The value of Y was determined from the empirical equation

$$Y = 1.0 - \left[0.41 + 0.35\left(\frac{D_2}{D_1}\right)^4\right]\left(\frac{\Delta p}{p_1\gamma}\right)$$

where

D_2 diameter of orifice, inches

D_1 diameter of pipe, inches

The value of the flow coefficient was obtained by extrapolating the data presented in reference 3. This value of the flow coefficient compared identically with that obtained using the data of reference 4.

Adjustable orifice. - The weight flow through the adjustable orifice was computed from charts and formulas supplied by the manufacturer.

Flow nozzle. - The weight flow through the flow nozzle was computed from the standard-orifice formula. Inasmuch as the vena contracta is negligible for such nozzles, a theoretical value ϕ was used instead of Y:

$$\phi = \left\{\frac{\gamma}{\gamma-1}\left(\frac{p_2}{p_1}\right)^{\frac{2}{\gamma}}\left[\frac{1-\left(\frac{p_2}{p_1}\right)^{\frac{\gamma-1}{\gamma}}}{1-\frac{p_2}{p_1}}\right]\right\}^{\frac{1}{2}}\left[\frac{1-\left(\frac{D_2}{D_1}\right)^4}{1-\left(\frac{D_2}{D_1}\right)^4\left(\frac{p_2}{p_1}\right)^{\frac{2}{\gamma}}}\right]^{\frac{1}{2}}$$

The approximate formula used by the manufacturer for weight-flow calculation is equivalent to the first term of the series expansion of the standard formula, and is nearly exact in the low range of nozzle pressure drops obtained in the engine tests.

Most of the runs were made with the survey probe an integral part of the nozzle, but 10 runs were made with the probe removed to determine the effect of the disturbances introduced by the probe on the weight flow through the nozzle.

The weight flows for each meter were assumed to be proportional to the weight flows given by the appropriate formulas, but the actual value of the flow coefficients were calculated from the experimental data. With the exception of the coefficient of the nozzle without the probe, these calculations were made using the simultaneous equations resulting from the application of the method of least squares. Since no coefficient was available for the adjustable orifice, a correction factor based on a reference value of 1.0000 was determined in the same manner. The correction factor and coefficients thus obtained give the best possible agreement between the weight flows measured by the different flow-metering devices. The determination of the flow coefficient for the nozzle without the probe was based on the weight flows obtained with the flat-plate orifice with its experimentally determined coefficient.

The probable error in determining the weight flows for each of the metering devices was determined with respect to the flow nozzle so that a comparison could be made between the weight flows determined by the NACA and those determined by the manufacturer. This variation was computed on the basis of the Gauss-Laplace law of frequency of errors.

RESULTS AND DISCUSSION

The coefficients for the metering devices determined by this investigation, their standard coefficients, and the ratio of the experimental to the standard coefficients are presented in the following table:

Coefficient	Flow nozzle (with probe)	Flow nozzle (without probe)	Flat-plate orifice	Adjustable orifice[1]
Experimental	0.9904	0.9917	0.6130	1.0037
Standard		.9950	.6170	1.0000
Ratio of experimental to standard coefficients		.9967	.9935	1.0037

[1]Correction factor

Although the survey probe occupied 1.77 percent of the nozzle-throat area, it decreased the weight flow only 0.13 percent. This result is in fair agreement with the theory of small obstructions in pipes.

The coefficient for the flow nozzle used by the manufacturer was 0.33 percent higher than the experimentally determined coefficient. The use of the experimentally determined correction factor for the adjustable orifice would yield weight flows 0.37 percent higher than those obtained in the compressor tests. The weight flows measured by these two meters should, therefore, vary by only 0.70 percent. The experimentally determined coefficient for the flat-plate orifice was 0.65 percent lower than the coefficient determined from reference 3.

The flow nozzle was used as a basis for determining the probable variation of the weight flows measured by the other air-metering devices so that a direct comparison could be obtained between the weight flows measured in the engine and compressor tests. These variations are presented in the following table:

	Probable variation with nozzle
Surveys across nozzle throat	±0.0050
Flat-plate orifice	±0.0032
Adjustable orifice	±0.0039

The variations among the meters are within experimental error. Although the average weight flows measured with the adjustable orifice are 0.70 percent lower than the weight flows measured with the flow nozzle, the probable variation about this mean is ±0.39 percent. The close agreement between the flow nozzle and the adjustable orifice clearly shows that the weight-flow discrepancy of approximately 4 percent between the results of the J33-A-23 compressor investigation by NACA and the engine tests conducted by the manufacturer was not caused by errors in flow metering. The greater part of the discrepancy is now attributable to the effect of inlet pressure on the compressor weight flow. As shown in reference 1, the compressor weight flow did change with inlet pressure but, because of power limitations, the maximum attainable inlet pressure was 14 inches mercury absolute as compared with 30 inches mercury absolute used in the engine tests.

SUMMARY OF RESULTS

Over a range of weight flows from 18 to 45 pounds per second the average weight flows measured with the adjustable orifice are

0.70 percent lower than the weight flows measured with the flow nozzle, the probable variation about this mean being equal to ±0.39 percent. The greater part of the discrepancy in weight flow of approximately 4 percent between the engine and compressor tests is therefore attributable to the effect of inlet pressure.

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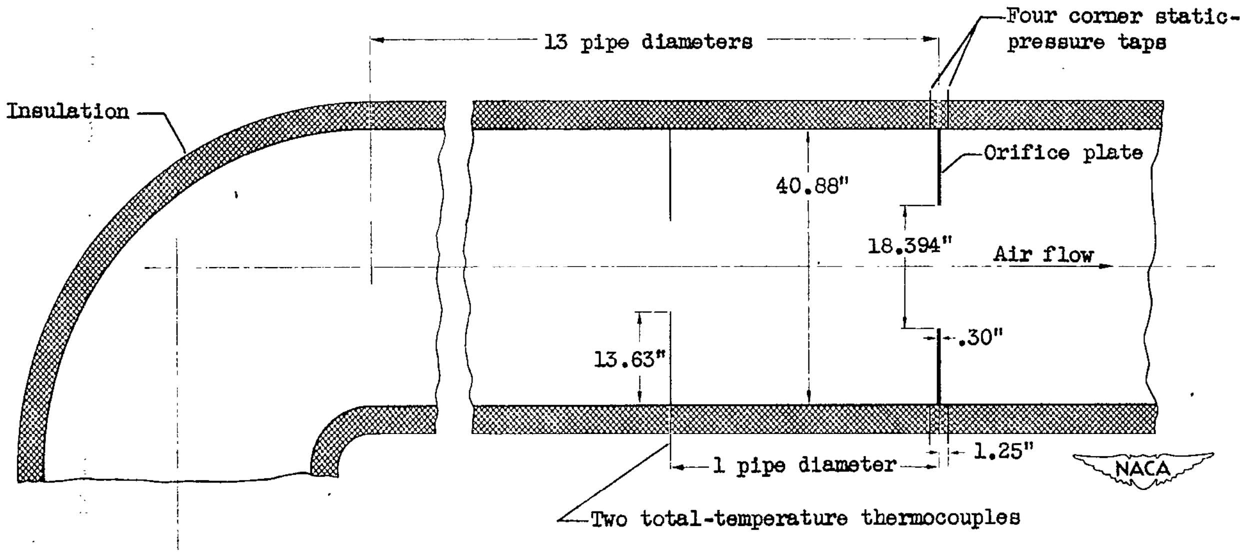


Figure 1. - Instrumentation of submerged flat-plate square-edge orifice.

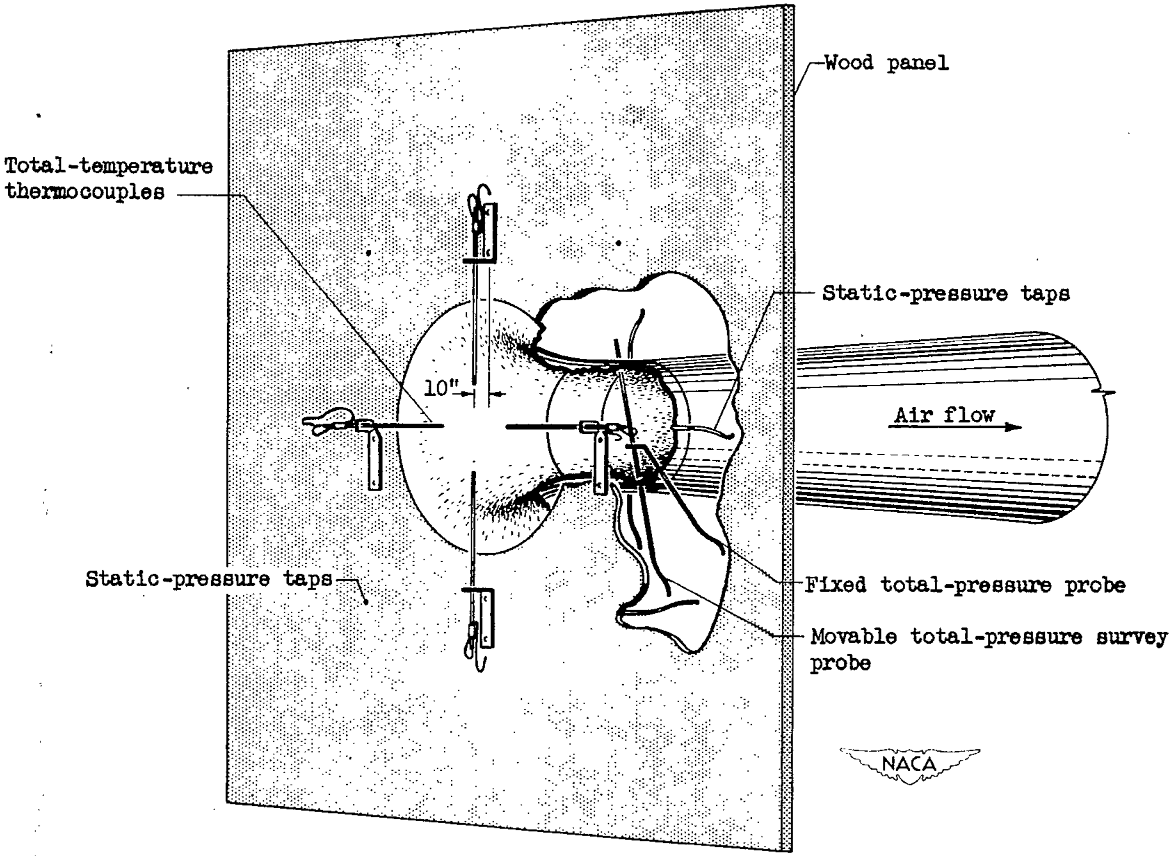
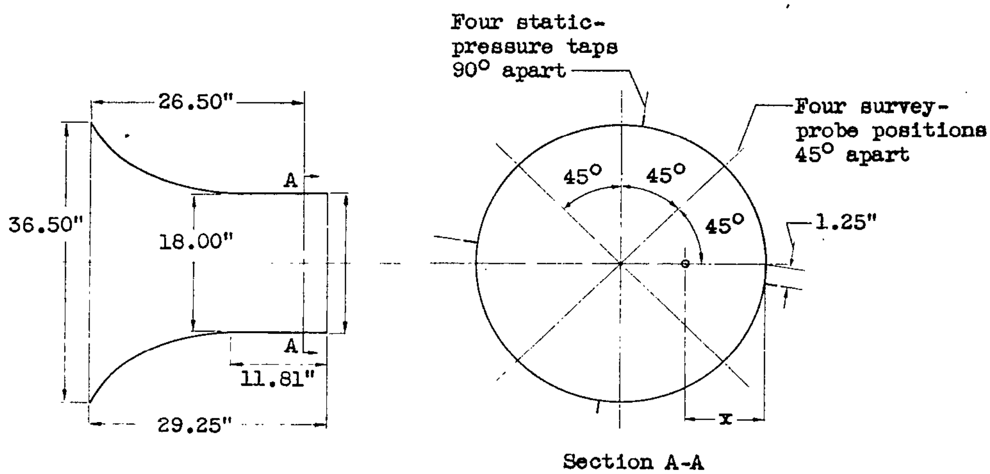


Figure 2. - Instrumentation of flow nozzle.



Station	x (in.)	Station	x (in.)	Station	x (in.)
1	0.015	13	4.875	25	13.875
2	.125	14	5.625	26	14.625
3	.250	15	6.375	27	15.375
4	.375	16	7.125	28	15.875
5	.625	17	7.875	29	16.375
6	.875	18	8.625	30	16.875
7	1.125	19	9.375	31	17.125
8	1.625	20	10.125	32	17.375
9	2.125	21	10.875	33	17.625
10	2.625	22	11.625	34	17.750
11	3.375	23	12.375	35	17.875
12	4.125	24	13.125	36	17.985

Figure 3. - Survey stations across nozzle throat.

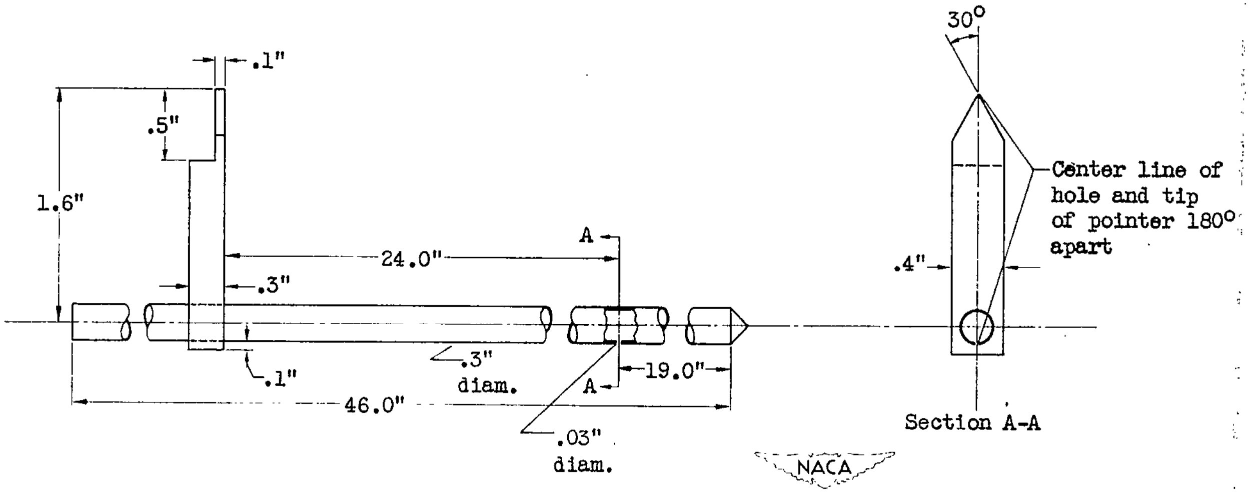


Figure 4. - Movable survey total-pressure probe.